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Effects of prescribed fires on first-year establishment of white oak (*Quercus alba* L.) seedlings in the Upper Piedmont of South Carolina, USA

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Abstract

Effects of prescribed fires on the 1-year establishment of white oak seedlings were investigated on the Clemson Experimental Forest, South Carolina, USA. Three stands, each consisting of a burn and a control treatment of about 1 ha in size, were examined in the study. On each burn and control treatment, six to eight dominant white oak trees were randomly selected along the slope and four 2-m radius quadrats were set up around each selected tree. Prescribed fire increased seedling biomass but it did not affect seedling mortality and root to shoot ratio. Effects of prescribed fire on seedling density, forest floor depth, and understory light intensity depended on stands, where burning increased seedling density in stands 1 and 3 but not in stand 2. Burning also reduced forest floor depth and increased understory light intensity in stands 1 and 3 but not in stand 2. Regression analyses indicated that forest floor depth and understory light intensity were significantly related to seedling density and biomass, with thinner forest floor and higher light intensity favoring the establishment of new oak seedlings. We conclude that burning can benefit the establishment of new white oak seedlings as long as it significantly reduces forest floor depth and increases understory light intensity.

Keywords: Oak regeneration; Prescribed fire; *Quercus alba*; Piedmont

1. Introduction

In the eastern United States, many studies have demonstrated the potential for widespread oak replacement by mesophytic tree species, especially on good quality sites (Loftis and McGee, 1993; Healy et al., 1997; McDonald et al., 2002). Anecdotal evidence suggests that the development of heavy midstory and understory coincides with the implementation of a fire exclusion policy in the 1920's (Abrams, 1992; Lorimer, 1993; Van Lear and Brose, 2002). Effective fire exclusion over the past 80 years has, therefore, contributed to the current stand and site conditions that are not conducive to oak regeneration.

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Indeed, upland oak stands harvested after 1930 are now frequently dominated by other hardwood species, while stands originating prior to 1930 are usually dominated by oaks (Heiligmann et al., 1985; Beck and Hooper, 1986; Hix and Lorimer, 1990; Abrams and Nowacki, 1992). Without effective management intervention, the area of upland oak ecosystems will continue to diminish as mature oak trees are harvested, killed by natural disturbances, or die from age-related causes (Healy et al., 1997).

Advance oak reproduction (i.e., seedlings, seedling sprouts, and saplings already established under the canopy) is considered a prerequisite for successful establishment of oak dominated stands (e.g., Carvell and Tryon, 1961; Sanders and Clark, 1971; Johnson et al., 2002). In general, oak regeneration failures are attributed to poor initial seedling establishment and slow juvenile growth (Johnson et al., 2002). In many mature oak stands, a closed understory dominated by later successional, shade-tolerant species often develops. The key concern about the increase of shade-tolerant species is that they can cause autogenic successional changes and the accompanying environmental conditions created by these species limits the establishment and development of oak advance regeneration (Abrams, 1992; Lorimer et al., 1994; Brose et al., 1999).

Various silvicultural treatments, including prescribed burning, herbicide application, understory thinning, or their combination, have been used to improve oak regeneration by reducing vegetation competition (e.g., Loftis, 1990; Barnes and Van Lear, 1998; Brose et al., 1999). Previous studies have shown the use of prescribed fire to be useful in developing oak regeneration (e.g., Barnes and Van Lear, 1998; Brose and Van Lear, 1998). These studies generally focused on how to use prescribed burning to enhance the relative competitiveness of advance oak regeneration. However, advance oak regeneration may be lacking or inadequately stocked in some stands currently dominated by oaks. In these stands, promoting the establishment of new oak seedlings becomes necessary.

Acorn survival and germination is a major factor influencing the development of advance oak regeneration (Johnson et al., 2002). Many acorns may be consumed by seed predators or fail to germinate into seedlings because of an unfavorable environment (e.g., Crow, 1988; Ostfeld et al., 1996). To provide a better environment for seedling recruitment, silvicultural practices such as understory light manipulation (Li and Ma, 2003) or soil scarification (Lhotka and Zaczek, 2003) have been successful. However, the effect of prescribed fire on the establishment of new oak seedlings has not been studied, perhaps due to the difficulty in predicting heavy mast years. Consequently, it is not clear whether prescribed fire can be used to promote the initial establishment of oak seedlings.

The primary objective of the study was to investigate the effects of prescribed fires on white oak seedling survival and growth during the first growing season following a heavy mast year. A secondary objective of the study was to determine if white oak seedling survival and growth during the first growing season were affected by forest floor depth, understory light intensity, and slope aspect.

2. Materials and methods

2.1. Study site

The study was conducted on the Clemson University Experimental Forest (CUEF) within the Piedmont physiologic province in northwestern South Carolina, USA (Fig. 1). CUEF has a humid temperate climate, with an average high of 25 °C in July, an average low of 7 °C in January, and an average annual precipitation of 1310 mm. It is characterized by rolling topography with soil associations dominated by Pacolet–Madison–Wilkes and Cecil–Hiawassee–Catuala (Byrd, 1972). Soils are strongly acidic, firm and clayey and are derived from gneiss, mica schist, hornblende schist and schist parent materials (Smith and Hallbeck, 1979). Similar to other areas of the Piedmont, CUEF land was farmed intensively until the 1930s for corn, cotton, and other row crops. Massive soil erosion resulted from these early agricultural practices (Trimble, 1974).

In the northern portion (Issaqueena Lake Area) of CUEF, three hardwood forest stands were selected for the study (Fig. 1). These stands were selected based on similarity of canopy composition, stand structure, and local topography. Forest structure of all selected stands was multilayered and dominated by oaks (*Quercus* spp.), hickories (*Carya* spp.), yellow-poplar

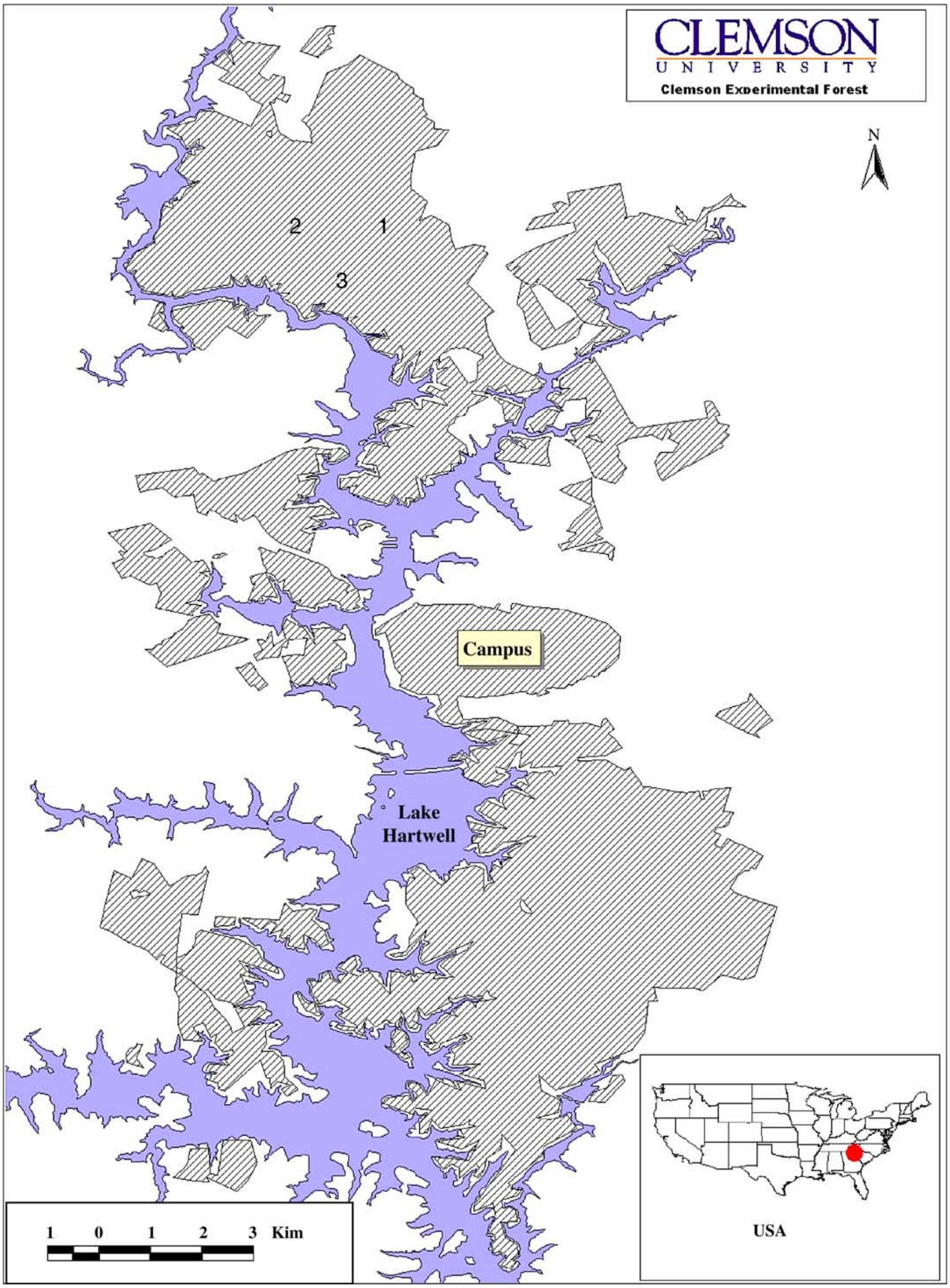

Fig. 1. Location of Clemson University Experimental Forest (CUEF) and the three study stands (1, 2, and 3) within CUEF. The insert indicates the location of CUEF in the United States.

(*Liriodendron tulipifera*) and a few relict pines (*Pinus* spp.) in the overstory. White oak accounted for 30% of total density and 35% of total basal area. Site index of white oak varied between 21 and 24 m at 50 year breast height age depending on slope position.

2.2. Prescribed fire treatment

Each stand was divided into approximately two halves, each with a minimum size of 1 ha. Prescribed fire was applied into one half (burned) and the other half was left unburned (control), for a total of six burn and control plots. The first burn treatments were implemented in February 1999 (stands 1, 2) and March 1999 (stand 3) with strip head fires set 5–10 m apart resulting in flame lengths generally greater than 30 cm. With the goal of achieving greater mortality of understory hardwood trees (<7.5 cm dbh) and preparing a more favorable seedbed, the second burn treatment was implemented in April 2000 for all three sites. Strip head fires were set 3–6 m apart and, because of lowered fuel loads, resulted in flame lengths generally less than 30 cm. Strip head fires were used to burn slopes and ridges, while backing fires burned more sheltered areas down to the stream. The 1999 winter fires only affected seedlings (woody, <50 cm tall) and herbaceous vegetation (Vandermst et al., 2004), while the 2000 spring fire resulted in the mortality of majority sapling-sized trees (Floyd, 2003). Both fires substantially reduced or completely eliminated the leaf litter (Floyd, 2003).

2.3. Study design

In 2002, white oak (*Quercus alba*) in CUEF had a heavy mast crop (Personal Communication, H.R. Still, South Carolina DNR), which provided an opportunity for studying the effect of prescribed fire on initial recruitment of white oak seedlings. In May 2003, six (stand 2) to eight (stands 1 and 3) dominant white oak trees were selected in each stand along transect lines parallel to the slope. Diameters of selected trees were measured and their trunks numbered using spray paint. Using each selected white oak tree as the center, two 8-m lines (one running along slope, another running at a 90° angle to the first line) were established. Four 2-m radius quadrats were established using the four ends of the two lines as their centers.

2.4. Data collection

In May, total germinated and surviving seedlings were counted and marked within each quadrat. Only seedlings from acorn crop of the fall 2002 were included in the study. In August, light intensity of each quadrat ($I_{cept.}$) was measured at 30 cm aboveground using a ceptometer (Decagon Devices Inc., Pullman, WA, USA). At the same time open-sky light intensity (I_{open}) was recorded using a LI1400 datalogger connected to a quantum sensor (Li-Cor Inc., Lincoln, NE, USA). Percent full sunlight (PFSL) received by each quadrat was calculated as

$$\mathrm{PFSL} = \frac{I_{cept.}}{I_{open}} \times 100 \quad (1)$$

All light measurements were taken during overcast days as recommended by a previous study (Parent and Messier, 1996). Immediately adjacent to each quadrat, depth of litter and duff was measured at four points and averaged for the quadrat. In October, each quadrat was revisited and white oak seedlings were recounted. Up to three seedlings per quadrat were randomly selected, excavated, and brought back to the laboratory to determine above- and below-ground biomass. In the laboratory, each seedling was washed, air-dried, and then oven-dried at 80 °C to a constant mass. Root and shoot components of each seedling were separated at the root-collar and weighed separately to determine biomass.

2.5. Data analysis

Seedling density in May (D_{May}) and October ($D_{Oct.}$) were calculated for each sampled tree based on individual quadrat data and expressed as stems/m^2. Based on seedling density in May and October, seedling mortality rate (MT) during the growing season was calculated as

$$\mathrm{MT} = \frac{D_{May} - D_{Oct.}}{D_{May}} \times 100 \quad (2)$$

Seedling biomass (SB) and root to shoot ratio (RSR) were also calculated for each sampled tree based on quadrat data. Aspects were grouped as north (including NE, NW, and E aspects) and south (including SE and SW aspects). No quadrat had a west aspect.

Analyses of variance (with stands as blocks, burned versus non-burned as treatments and trees as replicates) were conducted on white oak seedling measurements and site variables. If significant interactions between treatment and stand (block) were found, treatment effects (burned vs. control) were tested separately for each stand using a *t*-test. Scatterplots with locally weighted smooth curves were used to explore relationships between each oak seedling measure (density, mortality rate, biomass) and each site variable (forest floor depth and PFSL), based on which the appropriate regression models were selected. Non-linear and linear regression analyses were used to quantify these relationships. Separate variance *t*-tests were used to compare oak seedling measures between the two aspect groups (North versus South). Because statistical analyses on both May and October density yielded similar results, only results on October density were presented. All statistical analyses and graphics were conducted using SYSTAT 10.2 (SYSTAT Inc., 2002).

3. Results

Prescribed fire treatment affected density ($p = 0.005$) and biomass ($p = 0.019$), but it did not affect the mortality ($p = 0.680$) and root to shoot ratio ($p = 0.100$) of new white oak seedlings (Table 1). Burning also affected forest floor depth ($p = 0.001$) and understory light intensity ($p = 0.039$). Seedling biomass was higher in burned stands (0.68 g/seedling) compared to control (0.43 g/seedling). The effect of prescribed burning on seedling density, forest floor depth and understory light intensity, however, varied among stands ($p \leq 0.039$) (Table 1; Fig. 2).

Because of the significant interaction, treatment effects were separately examined for each stand. In stand 1, burning increased seedling density ($p = 0.012$), reduced forest floor depth ($p = 0.003$), and increased understory light intensity ($p = 0.028$) (Fig. 2). All burned quadrats were stocked with seedlings while only 47% of control quadrates were

Table 1
Probability values from analyses of variance for seedling and site variables with stands as blocks and prescribed fire as treatment

	Stand	Treatment	Stand × treatment
Seedling variables			
Seedling density (stem/m^2)	0.002	0.005	0.015
Mortality (%)	0.752	0.680	0.177
Seedling biomass (g/seedling)	0.030	0.019	0.709
Root to shoot biomass ratio	0.063	0.100	0.362
Site variables			
Forest floor depth (cm)	0.744	<0.001	0.001
% Full sunlight	0.004	0.002	0.039

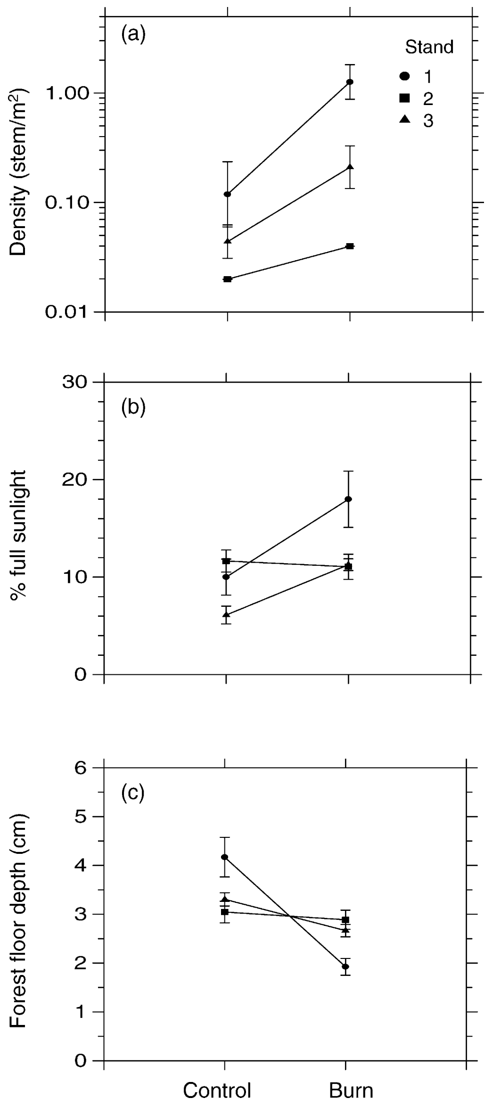

Fig. 2. Interactions of effects of fire and study stand: (a) white oak seedling density after the first growing season; (b) understory light intensity; (c) forest floor depth.

Table 2
White oak seedling density and growth at the end of the first growing season in relation to forest floor depth and understory light level: fitted regression equations and associated statistics

Equation	Sample size	R^2	rMSE
(1) $D_{Oct.} = 3.915(LFH)^{-2.176}$	44	0.412	0.751
(2) $D_{Oct.} = 0.172(PFSL)^{-0.785}(1.229)^{PFSL}$	44	0.731	0.513
(3) $SB = 0.883(LFH)^{-0.446}$	33	0.169	0.205
(4) $SB = 0.247 + 0.037(PFSL) - 0.001(PFSL)^2$	33	0.242	0.200

$D_{Oct.}$: density (stems/m^2) measure in October; LFH: forest floor depth (cm); PFSL: % full sunlight measured at 30 cm aboveground; SB: seedling biomass (g); rMSE: root mean square error. All models are significant ($p < 0.001$). R^2 reported are corrected R^2.

stocked with seedlings. In stand 3, burning increased density ($p = 0.062$) and understory light ($p < 0.001$), while it reduced ($p = 0.002$) forest floor depth (Fig. 2). About 80 and 44% of quadrats were stocked with seedlings in the burn and control treatments, respectively. Burning in stand 2 had no effect on seedling density, nor did it affect forest floor depth and understory light intensity (Fig. 2). Few seedlings were found in burn or control quadrats, and seedling stocking was extremely low (only 4 and 8% of quadrats stocked with seedlings on burn and control quadrats, respectively).

Seedling density and biomass were significantly related to both forest floor depth and understory light intensity (Table 2). With increasing forest floor depth, both density (Fig. 3a) and biomass (Fig. 3b) decreased, following a power relationship. Seedling density became consistently low when forest floor depth exceeded 3.5 cm (Fig. 3a). Similarly, both density and biomass increased with increasing understory light intensity (Fig. 4). Seedling density became consistently low when understory light intensity was less than 10% of full sunlight (Fig. 4a). Although not statistically significant, seedling mortality was positively correlated ($p = 0.095$) with forest floor depth and negatively correlated ($p = 0.194$) with understory light level. Despite the fact that south aspect had slightly higher density and slightly larger seedlings at the end of the first growing season, it did not significantly ($p \geq 0.072$) differ from north aspect.

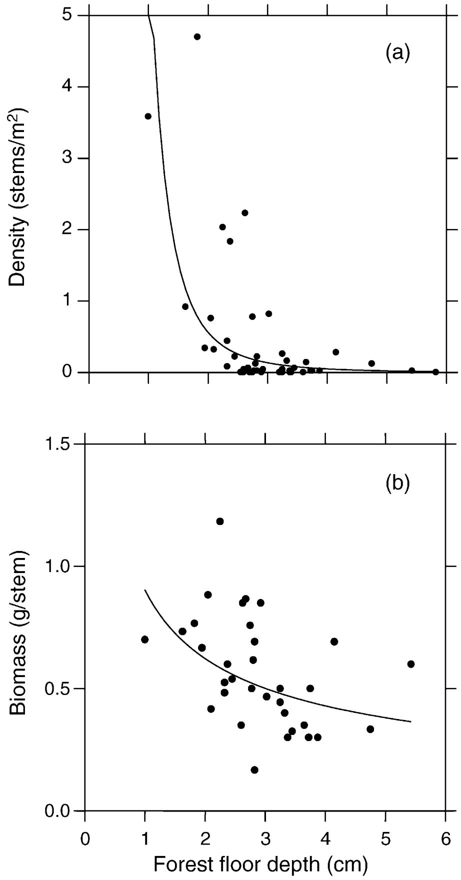

Fig. 3. White oak seedling density (a) and biomass (b) at the end of the first growing season in relation to forest floor depth. The smooth curve is the fitted regression equation specified in Table 2.

4. Discussion

It is generally acknowledged that fire exclusion has negatively affected the ability of oaks to regenerate under their own canopy (e.g., McGee, 1979; Abrams, 1992; Lorimer, 1993; Van Lear and Watt, 1993; Van Lear and Brose, 2002). In recent years, prescribed fire has been applied to promote oak regeneration in several studies (e.g., Barnes and Van Lear, 1998; Brose

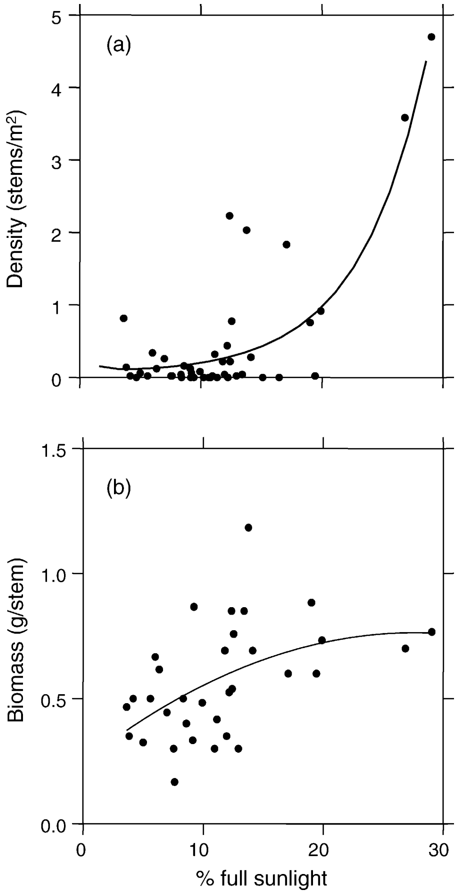

Fig. 4. White oak seedling density (a) and biomass (b) at the end of the first growing season in relation to understory light level. Understory light level is measured at 30 cm aboveground and expressed as % full sunlight. The smooth curve is the fitted regression equation specified in Table 2.

and Van Lear, 1998; Brose et al., 1999). However, these studies largely focused on how burning affects survival and growth of advance oak regeneration. Little is known concerning how initial recruitment of oak seedlings is affected by prescribed fire treatments.

Our study indicated that prescribed fire had a positive effect on both density and biomass of new oak seedlings after their first growing season. Compared to a recent study on first-year white oak seedling establishment after soil scarification (Lhotka and Zaczek, 2003), burning achieved a slightly better result, with more seedling recruitment (7700 versus 5164 stems/ha). Although mast acorn production was observed on each burned and control stands, our study could not determine whether the favorable effect of prescribed fire is attributed to an improved environment for seedling survival or better acorn quality. On one hand, much of the 1st year's growth could be made on reserves found in the acorns (Crow, 1988; Rogers, 1990), and burning might have resulted in better acorn quality. For example, selective logging (20–30% basal area removal) has resulted in more sound acorns of *Quercus costaricensis* (Guariguata and Saenz, 2002). On the other hand, prescribed fire did change the post-burn growth environment by reducing forest floor depth and increasing understory light intensity, and better seedling establishment was associated with reduced forest floor depth and increased understory light intensity.

Our study also indicated that effects of burning on density of new seedlings differed greatly among the three stands, suggesting fire behavior is an important factor to consider when using prescribed fires to promote the establishment of new oak seedlings. Fire behavior varies with many factors, and studying ecological effects of fire should not ignore distinctive fire behavior associated with each fire event (e.g., Albini, 1976; Alexander, 1982; Johnson and Miyanishi, 1995). Although quantitative description on the behaviors of each prescribed fire was not available, forest floor depth and understory light intensity measured on burn and control treatments suggested some important differences in fire effects among the three burned stands. Prescribed fires appeared more severe in stands 1 and 3 compared to stand 2. Differences in forest floor depth and understory light intensity remained significant between burn and control treatments 2 years after burning these stands. Considering both seedling density and growth increased with increasing understory light intensity and decreasing forest floor depth (Figs. 3 and 4), it was not surprising to find more seedlings on burned plots in stands 1 and 3. The higher seedling establishment on burned plots in stand 1 was likely a result of a thinner forest floor and higher understory light intensity after the burn. To promote the establishment of new oak seedlings, fire prescriptions should be aimed to achieve desired forest floor depth and understory light intensity, as observed on stand 1. However, results from our study could not be used to develop a practical guideline of prescribed burning to achieve the condition found in stand 1 because neither preburning stand information nor fire behavior were documented.

Our study found that white oak seedling density and biomass were significantly related to forest floor depth and understory light intensity. Some of these relationships, however, were not very strong (Table 2). There are inherent limitations to data sets derived from field studies that are subject to variation from a variety of non-controlled factors. Despite these limitations, relationships found in our study suggested that both forest floor depth and light intensity were important factors determining the initial success of white oak seedling recruitment.

Our study indicated that seedling recruitment was consistently low when forest floor depth exceeded 3.5 cm (Fig. 3a). Because litter averaged only 1.7–3.0 cm in depth on all stands regardless of burn, it should not have negatively affected seedling establishment. In an early study on *Quercus prinus*, Barrett (1931) reported that best acorn germination occurred where litter cover was between 2.5 and 5.0 cm in depth. In a recent study on *Quercus liaotungensis*, Li and Ma (2003) found that acorns covered by 2.5 cm litter germinated best and grew tallest, while acorns placed on litter germinated and grew the poorest. Therefore, differences in duff depth are likely responsible for the observed effect of forest floor depth, and we did find that burned plots had significantly thinner duff than control plots. Since no duff consumption was recorded in either 1999 or 2000 fires (Floyd, 2003; Vandermst et al., 2004), the reduced duff depth on burned plots was likely resulted from litter consumption. In the Piedmont, soil erosion is a concern when using prescribed fires. The fires prescribed in our study were carefully planned and conducted to avoid or minimize duff consumption. Our results suggested that it is possible to use prescribed fires to promote white oak seedling establishment without causing soil erosion.

Higher light intensity may have improved seedling recruitment and growth on burned plots, despite studies indicating that light availability may only limit growth after cotyledon reserves are depleted (Musselman and Gatherum, 1969; Crow, 1988). Light intensity near the forest floor of hardwood stands is often at or below the compensation point of oaks. The inability for oak seedlings to maintain a positive C balance under low light conditions may be the most likely reason for lack of oak advance regeneration (Musselman and Gatherum, 1969). In our study, seedling establishment became consistently low when understory light intensity dropped to <10% full sunlight. Although we have observed that 1-year old greenhouse grown white oak seedlings achieved positive carbon balance under 5% full sunlight (unpublished data), root competition could raise the compensation point from 6 to 15% in the case of *Quercus petraea* (Jarvis, 1964).

White oak generally has a good mast every 4–10 years (Rogers, 1990). It would be beneficial if prescribed fires could be timed to coincide with a good mast year to ensure acorns have a favorable environment for germination, survival and growth. In this study, prescribed fires were conducted about 2.5 years before the 2002 mast year. Depending on the initial consumption of forest floor and mortality of the under- and/or mid-story canopy, post-fire vegetation recovery and litter accumlation could have negated some beneficial effects provided by the initial burn. For example, at the time of this study, forest floor depth and understory light intensity were identical between burn and control in stand 2 although they remained different between burn and control in stands 1 and 3.

Because our study only presented results on seedling survival and growth after one growing season, the long-term development of these recruited seedlings is unknown. Given the higher light intensity and larger seedling size currently observed on burned plots, better survival and growth should be expected for those seedlings on burned plots, compared to control plots, in the next few years. The lack of significant difference in seedling mortality during the first growing season was likely attributed to the partial reliance of first-year seedlings on reserves in acorns.

5. Conclusions

White oak seedling establishment and growth during the first growing season benefited from prior prescribed fires. These fires reduced forest floor depth and increased understory light intensity, effects that remained significant at the time of the study. Seedling survival and growth were positively related to understory light intensity but negatively related to forest floor depth. Consistently low seedling establishment was associated with forest floor depths >3.5 cm and understory light intensities <10% full sunlight. For the purpose of promoting white oak seedling recruitment, prescribed fires should be conducted a year or two prior to a good mast year with sufficient intensity/severity for reducing forest floor depth and increasing understory light condition. Given the well-acknowledged role of fire in oak regeneration, more studies are needed to elucidate the effect of fire behavior on initial recruitment and subsequent development of oak seedlings, so that stand-specific fire prescription can be developed for practical application by forest managers.

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